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(71) We, NORTH AMERICAN ROCKWELL CORPORATION, a Corporation organized and existing under the laws of the State of Delaware, United States of America, of 2300 East Imperial Highway, City of El Segundo, State of California, United States of America, do hereby declare the invention, for which we pray that a patent may be granted to us, and the method by which it is to be performed, to be particularly described in and by the following statement:—

This invention relates to a solid state tunnel cathode.

For many applications, vacuum tubes using electron beams have not yet been replaced by solid state devices. In such applications, which include cathode ray video and storage tubes, and microwave beam tubes including magnetrons, travelling wave tubes, klystrons, and crossed field power generation tubes, the thermionic cathode still is used. This is so despite the fact that such thermionic cathodes have high operating temperatures (typically $\geqq$1,000°K) which make such emitters unsuitable for emission of electrons into other solids, which results in considerable cathode instability, and which accounts for considerable noisiness of the cathode.

A solid state electron emitter capable of operation at high current densities, low power, low noise, and at low temperatures is the ideal objective for a device to replace the thermionic cathode. The tunnel cathode represents a promising development in the search for such a cold emitter. However, limitations inherent in materials used for known tunnel cathodes have made such emitters impractical for device applications.

Known tunnel cathodes employ a three layer structure including a polycrystalline metal base, a very thin, electrically insulating polycrystalline film (typically an oxide of the metal used for the base) on top of the base, and a very thin metal emitter film atop the insulating barrier. Typical of such known tunnel cathodes is the aluminium-aluminium oxide-gold thin film device described by C. A. Meade, beginning on page 646 of the article, "Operation of Tunnel Emission Devices", Journal of Applied Physics, Volume 32 (1961).

The theory of operation of such a metal-insulator-metal tunnel cathode is described, e.g., in the article entitled, "Research in Tunnel Emission" by Wolfgang Feist, IEEE Spectrum, December 1964, beginning at page 57. This article also sets forth numerous short-comings of the known devices including the limitation that considerable scattering of the tunnelling electrons occurs in the polycrystalline insulating barrier and in the polycrystalline metal emitter layer. The resultant low electron transfer ratio severely restricts the efficiency of such known art tunnel cathodes and limits the maximum current density obtainable from such devices. These and other limitations of the known devices are discussed in detail hereinbelow, in conjunction with Figure 1, which illustrates a typical prior art tunnel cathode.

In accordance with the present invention, there is provided a tunnel cathode comprising a monocrystaline base, a thin film monocrystalline insulating barrier on the base and a thin layer monocrystalline semiconductive material disposed on the barrier serving as an emitter, the emitter having an electron density therein lower than the electron density of gold. The tunnel cathode of the

present invention has considerably reduced scattering in the insulating barrier and emitter layer. Further, use of a semiconductor emitter with a relatively high mean-free-path for tunnelling electrons enables the emitter layer to be thicker than that of the known devices with a concomitant decrease in resistive losses therein. Significantly higher electron current density is obtained from the present tunnel cathode than with known devices.

The entire structure of the invention may be fabricated on a single crystal, electrically insulating substrate. When an appropriate bias voltage is applied between the base and the emitter layers, electrons from the base tunnel through the insulating barrier and through the semiconductor emitter into the region above the emitter layer.

The single crystal tunnel diode may be constructed by epitaxial chemical vapour phase deposition of a metal (e.g., tungsten or molybdenum) on a single crystal, electrically insulating substrate such as sapphire. Next, a monocrystalline insulating barrier (e.g. of aluminium oxide) may be provided on top of the base by electron beam vacuum deposition. Finally, epitaxial deposition of a semiconductor (e.g., silicon) from the vapour phase provides a single crystal emitter at the top of the insulating barrier. (Other materials which may be used in the structure are discussed hereinbelow in conjunction with Figure 2).

Tunnel cathodes so produced have a variety of uses. For example, they may be used in place of a thermionic cathode in various types of video and controlled electron beam tubes. Further, the tunnel cathode according to the present invention may replace various special purpose electron sources such as Corona brushes in electrostatic devices, or may be used as an electron beam molecule ionizer in a mass spectometer or an ionization gauge.

The tunnel cathode of the present invention will now be described, by way of example only, with reference to the accompanying drawings in which:—

Figure 1 is a greatly enlarged perspective view, in partial section, of a known prior art tunnel cathode,

Figure 2 is a greatly enlarged perspective view, in partial section, of a monocrystalline tunnel cathode in accordance with the present invention,

Figure 3 is a schematic diagram showing the energy band structure of a typical tunnel cathode with no bias voltage applied,

Figure 4 is an energy band diagram of a tunnel cathode with a bias voltage greater than the equivalent work potential of the emitter applied between the base and the emitter layers,

Figure 5 is a greatly enlarged, simplified perspective view illustrating use of the tunnel cathode of the present invention as the electron source for a tube-like device incorporated into an integrated circuit and

Figure 6 is a perspective view, in partial section, of a storage tube utilizing the tunnel cathode of the present invention as a replacement for a flood gun.

A typical prior art tunnel cathode 10 is illustrated in FIG. 1. As shown, tunnel cathode 10 comprises a polycrystalline metal base 11, typically of aluminum. Atop base 11 is a very thin polycrystalline insulating barrier 12 (generally about 100Å in thickness), usually produced by oxidizing the metal of base 11. Polycrystalline metal emitter layer 13 also is very thin (about 100 Å thick), and typically is of gold. Battery 17 connected between base 11 and emitter 13 is used to provide the necessary potential to initiate tunneling.

A simplified energy versus distance diagram of a tunnel cathode is shown in FIG. 3. Electrons in base 11 and in emitter 13 occupy energy levels up to the respective Fermi levels E_{F_1} and E_{F_2}. Note that the Fermi levels of base 11 and emitter 13 each lie below the conduction band of the polycrystalline insulating barrier 12 and above its valence band. The work function Ø represents the characteristic amount of work required to remove one electron from the interior of emitter 13 to a position in a vacuum just outside the emitter.

When a voltage V_b is applied between base 11 and emitter 13 of tunnel cathode 10 (for example, by means of battery 17, as shown in FIG. 1) the Fermi level of the emitter is shifted down with respect to the Fermi level of the base by the amount qV_b where V_b is the applied battery voltage and q is the charge of an electron. Provided that the battery voltage V_b exceeds the height of the vacuum barrier voltage $[\frac{1}{q} V_b]$, the resultant energy band structure will resemble that illustrated in FIG. 4.

Assuming that insulating barrier 12 is sufficiently thin, electrons then can tunnel from base 11 to emitter 13. This results from the quantum mechanical wave properties of the electrons whereby they can penetrate as an attenuated wave through regions where electrons classically could not exist with positive kinetic energy.

The tunneling electrons arriving in emitter 13 are called "hot" electrons, since their energies are significantly above the Fermi level E_{F_2}. If the mean-free path of the "hot" electrons is large in comparison with the thickness of emitter 13, a portion of these hot electrons will travel through emitter 13 and

escape into the vacuum region therebeyond. Those electrons which cannot be emitted, either because too much of their energy has been lost from collisions in emitter 13 or because they arrived at emitter 13 initially with too little energy to go over vacuum barrier Ø, eventually will fall below the Fermi level E_{F_2} and will be conducted away through battery 17.

The above description is based on an idealized model of the tunnel cathode shown in FIG. 1. However, a more realistic evaluation of the device indicates the shortcomings typical of the prior art. First, consider the requirement for field emission of electrons from metal base 11. An approximate description of the requirements for field emission from base 11 into insulating barrier region 12 is provided by the following Fowler-Nordheim relationship for the current density J emitted from a metal into a vacuum:

$$J = a E_o^2 e^{-b/E_o} \qquad (1)$$

In equation (1), a and b are constants, the later depending on the work function of the metal, and E_o is the electric field gradient at the emitting surface of the metal (corresponding to surface 14 in FIG. 1). Note that the current density J is independent of temperature, as long as the thermal energy is small compared with the energy required to surmount the work barrier at the surface of the metal. Numerical evaluation of equation (1) indicates that significant currents are not emitted from metal base 11 until E_o reaches values of 10^7 volts per centimeter.

In the tunnel cathode of FIG. 1, the field gradient E_o at surface 14 is provided by the the electric field resulting between base 11 and emitter 13 when battery 17 is connected.

Although equation (1) does not directly place constraints on the thickness of insulating barrier 12, the high field gradient required across surface 14 can be achieved with reasonable bias potential V_b only with a very thin insulating barrier film 12. As an example, the highest dielectric strength for a thick mica sheet is about 10^6V/cm. However, when a dielectric is very thin its dielectric strength increases greatly, thus the required high field gradient E_o has been achieved in the prior art by restricting the thickness of insulating barrier 12 to very thin films, perhaps less than 100 Å.

With an insulating barrier 12 having a sufficient dielectric strength to allow a field gradient E_o greater than 10^7 volts per centimeter to be achieved at interface 14, quantum mechanical conditions allow electrons near the Fermi band in base 11 to tunnel through the forbidden region of insulating barrier 12. Band theory, applied to such electrons tunneling through insulating barrier 12, requires that the electrons be considered moving as plane waves. In the conduction band of the insulating barrier, the electron plane wave normally is treated as traversing an ideal periodic lattice, with interference phenomena occurring for which the ratio of the wavelength to the periodicity distance is the decisive parameter. However, in the real case, it is doubtful that this is the picture.

Insulating barrier 12 of prior art tunnel cathode 10 is polycrystalline, and hence includes a large number of crystal grain boundaries and lattice defects. In such material, the electrons are not well shielded and may act as space charge centers distorting the surroundings. Moreover, interaction between electrons and nonperiodic lattices occur. In particular, hot electrons will be scattered by elastic electron-phonon collisions and by other interactions with lattice defects and crystal grain boundaries in barrier layer 12.

Yet another limitation of the prior art polycrystalline insulating barrier 12 is that polycrystalline materials include trapping sites, the presence of which may lead to localized breakdown of the barrier at electric field levels significantly below that required to obtain emission from base 11. Moreover, the space charge effect of such trapping sites limits the current which can flow through insulating barrier 12.

The hot electrons which do survive passage through insulating barrier 12 are subjected to even more severe scattering losses in polycrystalline metal emitter layer 13. Typically, only 0.1 percent or less of the hot electrons which penetrate into emitter layer 13 emerge into the vacuum therebeyond. This percentage may be expressed as a transfer ratio or ratio of the number of electrons emergent from the emitter 13 to the number of electrons entering emitter 13 from insulating barrier 12 through interface 15.

In the prior art, metal emitter 13 typically was of polycrystalline gold. The transfer ratio of a gold film 100 Å thick is approximately 10^{-3}. For a thickness of 150 Å the transfer ratio of gold barrier layer 13 drops to about 10^{-4}; at 200 Å thickness the transfer ratio is about 5×10^{-6}, a very severe loss indeed. Thus, for reasonable transfer ratios in a polycrystalline gold emitter 13, it is imperative that the layer be less than about 100 Å thick.

The low transfer ratios of polycrystalline metal films result from severe scattering of the tunneling electrons by electron-phonon and electron-electron collisions. When the electrons are traveling at energies near the Fermi level E_{F_2} of emitter 13, the primary

collisions are elastic electron-phonon. However, when the tunneling electrons have energy in excess of E_{F_3}, the mean-free path for electron-electron collision decreases considerably and for excess energies in the order of 3 electron-volts, scattering is attributed primarily to inelastic collisions with conduction electrons. Thus, the motion of hot electrons is essentially ballistic.

The number of electrons transferred through metal-emitter layer 13 at a particular energy level decreases with distance X according to the factor $E^{-X/\lambda}$ where $\lambda = (1/3\lambda_E\lambda_P)^{0.5}$ for the diffusion case and $\lambda = \lambda_E$ for the ballistic case. (λ_P = the mean-free path for electron-phonon collisions; λ_E equals the mean-free path for electron-electron collisions.) For gold, λ_P is approximately 240 Å and λ_E is approximately 100 Å. Since the hot electrons traveling through gold emitter 13 are in excess of Fermi energy E_{P_2}, the primary collisions are electron-electron; the fact that λ_E is less than 100 Å is consistent with the low transfer ratio of gold noted above.

Moreover, since metal layer 13 is polycrystalline, severe scattering due to lattice defects, crystal grain boundaries, and the presence of foreign ions and trapping sites also is common.

Additional problems arise when emitter layer 13 is made extremely thin, as required for reasonable electron transfer ratios. First, the area resistivity is quite high, thus when electrons captured in emitter 13 are conducted into battery 17 (see FIG. 1) excessive ohmic heating may occur in the film. This limits the maximum current density obtainable from the device and causes the maximum current density during continuous operation to be significantly lower than that obtainable during pulsed operation. Moreover, such thin emitter 13 films are susceptible to damage by exposure to air and water vapor.

Typical emission densities obtained from prior art, aluminum-aluminum oxide-gold tunnel cathodes (configured as shown in FIG. 1) are 10 ma/cm^2 for continuous operation and 10 A/cm^2 under pulsed conditions.

The difficulty associated with prior art tunnel cathodes (typified by the device of FIG. 1) are overcome using the inventive tunnel cathode structure illustrated in FIG. 2. As shown therein, tunnel cathode 20 comprises a metal base 21 of monocrystalline metal. Epitaxially disposed on monocrystalline base 21 is insulating barrier 22, itself monocrystalline. Atop insulating barrier 22 is monocrystalline emitter 23, which is of a semiconductor material. The entire structure may be fabricated on a monocrystalline substrate 27 of electrically insulating material. Tunnel cathode operation is obtained when an appropriate bias voltage V_b is applied between base 21 and emitter 23 by means of battery 17′.

The energy band diagrams of FIGS. 3 and 4 are applicable to the inventive tunnel cathode of FIG. 2. However, very significant differences exist between the operation of the prior art polycrystalline cathode and the novel monocrystalline tunnel cathode illustrated in FIG. 2.

With respect to insulating barrier 22, when made of monocrystalline material, it is able to withstand significantly higher electric field gradients without breakdown than is a polycrystalline barrier. This, of course, results from the absence of trapping sites within the monocrystalline material. Moreover, since a monocrystalline material has few if any lattice defects or crystal grain boundaries, electron scattering within insulating barrier 22 is substantially less than in the polycrystalline insulating barrier 12 of the prior art. Moreover, a monocrystalline structure has inherently greater mechanical stability than does a polycrystalline material. Hence, a monocrystalline insulating barrier is much less subject to mechanical breakdown under the stress of the high electric field required for electron emission from the base.

With respect to emitter layer 23 the improvement in performance of the inventive tunnel cathode of FIG. 2 is even greater. First, recall that for hot electrons the primary scattering in emitter layer 23 is due to electron-electron collisions. Comparing the properties of gold films with those of a semiconductor, it is noted that the electron density in gold at room temperatures is about 10^{28} electrons/meter^3 whereas the carrier density for even heavily doped silicon or germanium would not exceed about 10^{25} electrons/meter^3. Since the ballistic electron-electron collision probability varies inversely with conduction carrier density, the result is that the mean-free path λ_E for silicon is much greater than the mean-free path λ_E for gold, λ_E for silicon having a value on the order of 1,000 Å. For silicon, the mean-free path for electron-phonon collisions λ_P also is on the order of 1.00Å.

The expected transfer ratio for silicon can be computed from the equation:

$$\frac{J_{IN}}{J_{OUT}} = e^{-\frac{3X}{(\lambda_E\lambda_P)1/2}} = e^{-\frac{3X}{100}} \qquad (2)$$

For a 1,000 Å film (0.1 micron), a transfer ratio of 0.74 may be expected. This is considerably greater than that exhibited by a

100 Å gold film such as utilized in the prior art tunnel cathode of FIG 1.

Since the mean-free path for electron-electron and electron-phonon collisions are significantly higher in monocrystalline silicon than in a polycrystalline metal, the thickness of emitter layer 23 may be substantially greater than that of prior art metal emitter layer 13. This greater allowable thickness offsets the effect of lower conductivity in the monocrystalline semiconductor emitter 23 which otherwise may result in current limiting if the electrons trapped in the emitter are not returned to ground. Moreover, since far fewer hot electrons are absorbed in monocrystalline semiconductor emitter 23 than in polycrystalline metal emitter 13, resistive heating in the emitter layer is significantly reduced, thus making the thermal dissipation requirements of the silicon film less severe than those of prior art metal emitter 13.

Use of high resistance semiconductor material for emitter layer 23 may effect the potential profiles both across the surface of the emitter and in a direction normal to the surface. Thus it may be desirable to use a graded emitter wherein the conductivity increases from a minimum at interface 25 to a maximum at the emitting surface 26. Such a graded resistivity profile easily may be obtained during the epitaxial growth from the vapor phase of emitter 23, as described hereinbelow.

When using 0.1 micron of silicon for emitter 23, continuous emission densities of about 1 A/cm^2 may be expected, as computed using equation (1) (corrected for emission into insulating barrier 22 rather than into a vacuum) and the monocrystalline silicon transfer ratios described hereinabove. This is to be compared with outputs of 10^{-2} A/cm^2 for prior art tunnel cathodes such as that shown in FIG. 1. An emission density of 1 A/cm^2 is quite sufficient to compete with thermionic cathodes.

Monocrystalline tunnel cathodes in accordance with the present invention may be fabricated from various combinations of materials including but not limited to those listed in the following Table I.

TABLE I

Substrate	*Base*	*Insulating Barrier*	*Emitter*
sapphire	tungsten	aluminum oxide	silicon
sapphire	tungsten	aluminum oxide	germanium
sapphire	tungsten	aluminum oxide	zinc sulfide
sapphire	tungsten	aluminum oxide	gallium arsenide
sapphire	molybdenum	aluminum oxide	silicon
sapphire	molybdenum	aluminum oxide	germanium
sapphire	molybdenum	aluminum oxide	zinc sulfide
sapphire	molybdenum	aluminum oxide	gallium arsenide
magnesia	tungsten	magnesium oxide	silicon
magnesia	tungsten	magnesium oxide	germanium
magnesia	molybdenum	magnesium oxide	silicon
magnesia	molybdenum	magnesium oxide	germanium

Moreover, it also is possible to utilize a monocrystalline semiconductor for base 21. Thus the inventive tunnel cathode also may be fabricated of the following combinations of materials:

Si/SiO/Si, W/SiO/Si, W/SiO/^{Ge}.

With respect to monocrystalline base 21 (see FIG. 2), the material used should be one having a work function of sufficiently low value so that a reasonable bias voltage V_b will ensure tunneling. Moreover, the material should be one which can be deposited in single crystal form on an appropriate electrically insulating single crystal substrate material.

Among the materials which can be used for base 21 are tungsten and molybdenum. As described by Arnold Miller et al beginning on page 263 of the book "Metallurgy of Advanced Electronic Materials", Volume 19, *Interscience Publishers,* (1963), single crystal tungsten may be deposited on an electrically insulating substrate of single crystal sapphire by hydrogen reduction of WF_6. Crystallographic orientations observed as a function of substrate face where:

$$(111)_W \,//\, (10\bar{1}1)_{Al_2O_3};\ (001)_W \,//\, (\bar{1}012)_{Al_2O_3};$$

$$(113)_W \,//\, (11\bar{2}3)_{Al_2O_3};\ (111)_W \,//\, (0001)_{Al_2O_3}.$$

Single crystalline tungsten also can be prepared by the same chemical vapor phase deposition process on a substrate of magnesia.

The ability to control crystallographic orientation of the metal used for monocrystalline base 21 is important because the work function of base 21 is dependent on the crystallographic plane parallel to interface 24. This dependence (for tungsten) may be seen from the data in Table II below derived from field emission measurements.

TABLE II

Tungsten Crystallographic Plane	Electronic Work Function (in electron volts)
111	4.39
233	4.46
123	4.52
112	4.65-4.88
011	5.70-5.99
116	4.29
111	4.39
112	4.65
Polycrystalline	4.50

As noted above, the electronic work function is the characteristic amount of work required to remove one electron from the interior of base 21 to a position just outside thereof.

Molybdenum (with a work function of about 4.23 electron volts) also has been prepared in single crystal form on a number of electrically insulating substrates including sapphire, MgO, BeO, and magnesium aluminate spinel. In each case, epitaxial deposition was carried out by pyrolysis of molybdenum hexachloride in a hydrogen atmosphere.

Various other materials may be selected for monocrystalline base 21. In this regard, following Table III below lists the electronic work functions of selected materials which may be prepared in single crystal form for use as base 21.

TABLE III

Material for Base 21	Electronic Work Function (in electron volts)
W	4.50
Ge	4.78
Si	4.02
Bi	4.28
Au	4.58
Mo	4.23
Ni	4.74
Fe	4.70

The work functions listed in Table III are approximate values; the exact value will vary somewhat depending on the crystallographic orientation of base 21.

Insulating barrier 22 preferably is of a material having a band gap sufficiently wide so that, with bias voltage applied, the distance between the Fermi level E_{F_1} of base 21 and the upper edge of the valence band of barrier 22 is larger than the vacuum work function of emitter 23. Of course, insulating barrier 22 also should comprise a substance which can be deposited epitaxially on the material selected for monocrystalline base 21. Materials which meet both requirements for insulating barrier 22 include, but are not limited to, Al_2O_3, MgO, SiO, ThO_2, TiC, and BaS.

Monocrystalline insulating barrier 22 may be prepared by epitaxial deposition onto upper surface 24 of the previously prepared combination of substrate 27 and monocrystalline base 21. For example, Al_2O_3 can be deposited in single crystal form onto monocrystalline base 21 of tungsten or molybdenum prepared as described hereinabove. To achieve such epitaxy, the combination of substrate 27 and base 21 is placed in a high vacuum chamber and heated to a temperature above the epitaxial temperature of about 800°C. A thin film of Al_2O_3 then is deposited by electron beam vacuum techniques. Alternatively, Al_2O_3 may be deposited in single crystal form by chemical vapor phase deposition using a gaseous aluminum-alkyl mixed with CO_2 and hydrogen as the starting material. Single crystal aluminum oxide films of thicknesses up to 200 Å have been prepared in this manner; such thickness is commensurate with or greater than that required for insulating barrier 22.

Monocrystalline semiconductor emitter layer 23 may be of silicon, germanium, zinc sulfide or gallium arsenide. Silicon has been deposited epitaxially on various insulating materials including $\alpha-Al_2O_3$ by hydrogen reduction of $SiCl_4$ or $HSiCl_3$, and by thermal decomposition of SiH_4.

The silicon orientation achieved will depend on the orientation of the aluminium oxide insulating barrier 22, which in turn will depend on the orientation of base 21. Typical silicon orientations on $\alpha-Al_2O_3$ include, but are not limited to,

$(100)_{Si}//(10.2)_{Al_2O_3}$; $(111)_{Si}//(11.0)_{Al_2O_3}$; $(111)_{Si}//(00.1)_{Al_2O_3}$.

Germanium may be produced epitaxially by pyrolysis of germane. As with silicon, the orientation of this chemical vapor phase deposited germanium is controlled by the orientation of the underlying single crystal deposition surface.

During the chemical vapor phase deposition of emitter 23, a resistivity changing dopant of a kind well known to those skilled in the art may be introduced into the deposition chamber to control the resistivity of the deposited semiconductor. By changing the concentration of the dopant as emitter 23 increases in thickness, a controlled, graded resistivity profile may be produced.

While the preceeding discussion has emphasized the use of a metal for monocrystalline base 21, it also is possible to use a semiconductor material such as silicon or germanium for this monocrystalline layer.

The inventive tunnel cathode described hereinabove finds a wide variety of applications, only a few of which are described be-

low. For example, a tunnel cathode in accordance with the present invention may be used as an electron source in a tube to perform circuit functions not convenient with solid state devices. Such functions include, e.g., the control of high voltages, amplification in the UHF or VHF region (using negative grid tubes), and control of signals which naturally are voltages rather than currents.

Tubes using the inventive tunnel cathode even may be hybrid into an integrated microelectronic circuit. An example of such a hybrid circuit is shown in FIG. 5. In particular, integrated circuit 40 is mounted on base 41 and hermetically sealed inside housing 42 so that the entire interior region may be evacuated. Integrated circuit 40 may be fabricated on a monocrystalline electrically insulating substrate 43 (e.g., of sapphire) and may contain various islands 44 and 44′ of a semiconductor such as silicon, epitaxially grown on substrate 43. Islands 44 and 44′ may be appropriately processed to provide diodes, transistors, or other semiconductor circuit elements.

Tunnel cathode 45 (having the characteristics described in conjunction with FIG. 2 above) may be grown epitaxially directly on substrate 43 and may contain monocrystalline metal base 46, monocrystalline insulating barrier 47, and monocrystalline emitter 48, corresponding respectively to layers 21, 22, and 23 in the embodiment of FIG. 2.

Electrons from tunnel cathode 45 emerge from the top surface of emitter 48 and may be used in a tube-like structure comprising grid 49 and plate 51 which are suspended above tunnel cathode 45 by means of tripod legs 50a, 50b, and 50c. Grid 49 is electrically insulated from legs 50a, and 50b and electrically connected to 50c. Similarly, plate 51 is electrically insulated from legs 50b and 50c and electrically connected to leg 50a, thus legs 50a and 50c provide electrical connection for the grid and plate respectively. Thin film electrical conductors 52 and 52′ provide inter-connections between the various elements of microcircuit 40. Since the entire hybrid circuit 40 is contained in an evacuated hermetically sealed structure 42, no additional housing is required for the tube.

Tunnel cathodes made in accordance with the present invention also may be used to inject electrons directly into a solid rather than into a vacuum. Thus tunnel cathodes such as that shown in FIG. 2 may be used as part of a solid state tunnel emission triode prepared by providing an additional insulating layer (not illustrated) over emitter 23 and overlaying this additional insulating layer with a final metal film to serve as a collector for the triode. Electrons possessing sufficient momentum to overcome the work function of emitter 23 now find themselves in the conduction band of the second insulator and will be accelerated toward the positively biased collector. In an appropriate circuit, current gain may be realized. Moreover, appropriate modulation of the bias voltage V_b applied to the tunnel cathode also may permit modulation of the electron stream.

Yet another possible application of the inventive tunnel cathode of FIG. 2 is as part of an electroluminescent device. For example, a phosphor layer (not illustrated) may be evaporated on top of emitter 23 and a transparent conducting film deposited on top of the phosphor layer. By impressing a sufficiently high voltage across the phosphor, electrons from the tunnel cathode may be accelerated to an energy at which they can energize defects in the phosphor crystal lattice, thereby causing light emission. Such structures may be attractive as illumination panels, replacing the very inefficient prior art electroluminescent panels which depend on an alternating electric field gradient in the phosphor to produce light.

Where a tunnel cathode according to the invention is used as a source of electrons within a tube, it is preferred that the base should have an electronic work function of between four and six electron volts and that the emitter should have a hot electron transfer ratio greater than 0.005.

In many applications, the inventive tunnel cathode described hereinabove can replace a conventional thermionic cathode, often with improved performance. One such application is a flood gun in a storage cathode ray tube; such an application is illustrated in FIG. 6. As shown in FIG. 6, storage cathode ray tube 55 comprises base 56, glass outer shell 57, and storage screen 58. A concentrated stream of electrons, used for reading and writing, is produced by conventional electric field deflection plates 60 and by immersion magnetic lens and beam deflection assembly 61.

A tunnel cathode in accordance with the present invention serves as flood gun 62 (see FIG. 6). Flood gun 62 may be substantially annular in shape with a central opening to allow passage of the electrons from gun 59. Flood gun 62 comprises monocrystalline substrate 63, monocrystalline metal base 64, monocrystalline insulating barrier 65, and monocrystalline emitter 66, respectively equivalent to layers 27, 21, 22 and 23, of the tunnel cathode shown in FIG. 2. Appropriate electrical connections to the various components within tube 55 may be made via pins 67 extending from base 56.

Use of the inventive tunnel cathode as flood gun 62 in storage tube 55 has a number of outstanding advantages over conventional flood guns. In particular, it is desirable

that flood guns provide a uniform electron cloud over the entire surface of screen 58. Such a uniform cloud is extremely difficult to achieve conventionally since the electrons from prior art flood guns, originating from a small surface area, were focused at least partially by magnetic lens and beam deflection assembly 61. In the past, this often has resulted in the requirement that the lens and beam assembly be shut off at times when the flood gun was in operation.

Since essentially uniform electron emission occurs over the entire, large surface of tunnel cathode flood gun 62, the electrons experience little or no focusing due to the effect of magnetic lens 61 and provide a uniform electron cloud at the surface of screen 58. Moreover, the continuous emission density from flood gun 62 need not be very high. For example, tunnel cathode flood gun 62 may have an area of from 1 square inch to 10 square inches. At an emission density of only 1 ma/cm^2, flood gun currents of from 6.5 to 65 ma can be obtained; such currents are more than satisfactory for flood gun applications.

Other applications of the inventive solid state tunnel cathode include use as electron beam molecule ionizers in mass spectrometers and ionization gages, as a replacement for beta ray sources in TR boxes (where electrons must continually be introduced to insure that the device will fire properly), and as a replacement for Corona brushes in such applications as VanDeGraff generators, air particle ionizers in precipitors, and aircraft electrostatic discharge systems. The inventive tunnel cathode also may be used as an electron source for a secondary emission amplifier. Such amplifiers require low input current density and increase the density to values usable even in power tubes. For example, a six stage bucket dynode multiplier having a voltage drop of 900 volts across the dynode chain can multiply a tunnel cathode emission density of 1 ma/cm^2 to an output of 7 A/cm^2. This current output density is competitive with the best thermionic cathodes ever built.

Still another use of the tunnel cathode is as an M-type non-reentrant crossed field power amplifier. These devices utilize an electric field generated by a slow wave structure, to cause electrons to move along cycloidal trajectories with increasing energy. In such a device, the inventive tunnel cathode could be used both as the original electron source and also as a source to inject electrons into the interaction space, substantially reducing a loss problem associated with prior art crossed field amplifiers.

WHAT WE CLAIM IS:—

1. A tunnel cathode comprising a monocrystalline base, a thin film monocrystalline insulating barrier on the base and a thin layer monocrystalline semiconductive material disposed on the barrier serving as an emitter, the emitter having an electron density therein lower than the electron density of gold.

2. A tunnel cathode according to claim 1, including an electrically insulating substrate material beneath said base and attached thereto.

3. A tunnel cathode according to claim 1 or 2 wherein the base is of tungsten, molybdenum, gold, bismuth, nickel, iron or silicon, the barrier is of aluminium oxide, silicon monoxide, magnesium oxide, thorium oxide, titanium carbide or barium sulfide, and the semiconductive emitter material is silicon, germanium, gallium arsenide or zinc sulfide.

4. A tunnel cathode according to claim 1, 2 or 3 including means connected to the emitter and base for providing a bias voltage to the tunnel cathode said bias voltage being greater than the work function of the base.

5. A tunnel cathode according to any of the preceding claims wherein the carrier density in the emitter material does not exceed 10^{23} electrons per cubic meter.

6. A tunnel cathode according to any of the preceding claims wherein the emitter has a graded resistivity profile.

7. An electron tube having a source of electrons within the tube comprising a tunnel cathode according to any of the preceding claims wherein the base has an electronic work function of between four and six electron volts and the emitter has a hot electron transfer ratio greater than 0.005.

8. A tunnel cathode substantially as described with reference to Figures 2, 5 or 6 of the accompanying drawings.

9. A vacuum tube substantially as described with reference to Figure 6 of the accompanying drawings.

10. A source of electrons comprising a tunnel cathode according to any of claims 1 to 8 in combination with means for utilizing electrons provided by the source.

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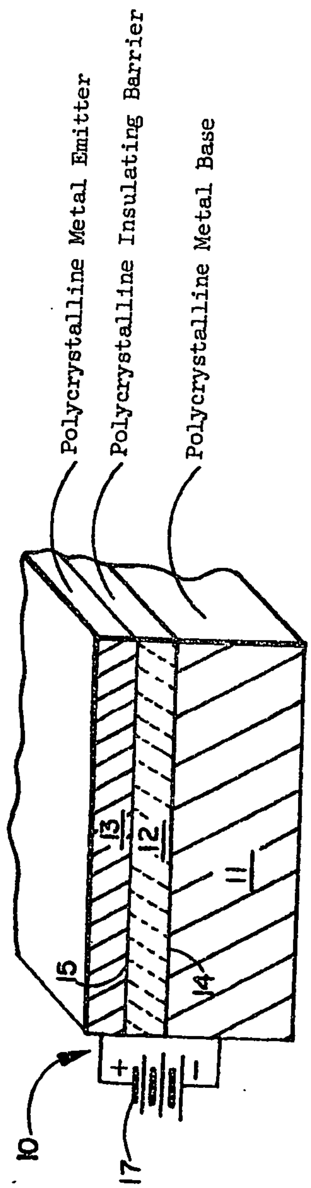
1,223,729 COMPLETE SPECIFICATION
3 SHEETS
This drawing is a reproduction of the Original on a reduced scale.
SHEET I



PRIOR ART

FIG. 1

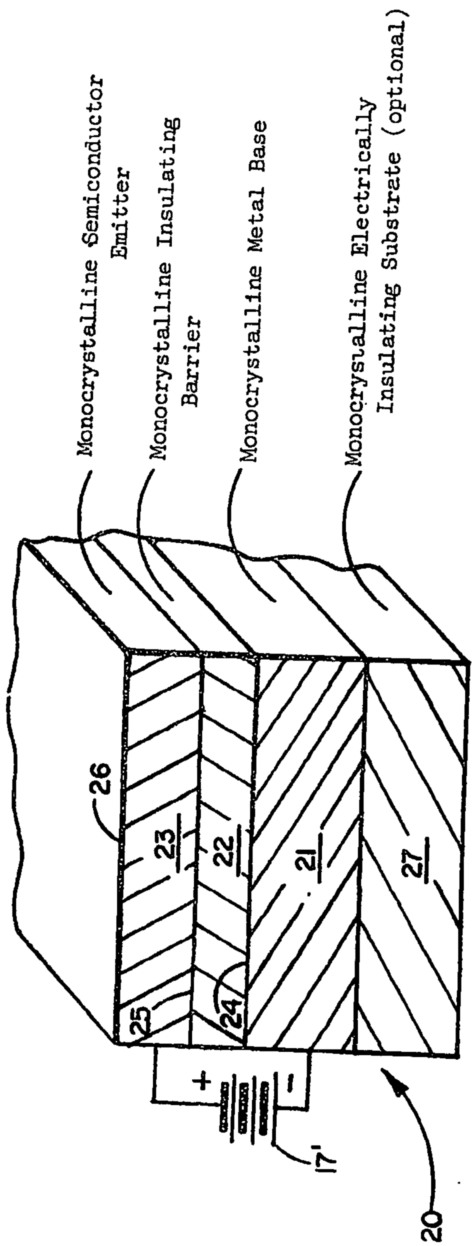


FIG. 2

FIG. 3

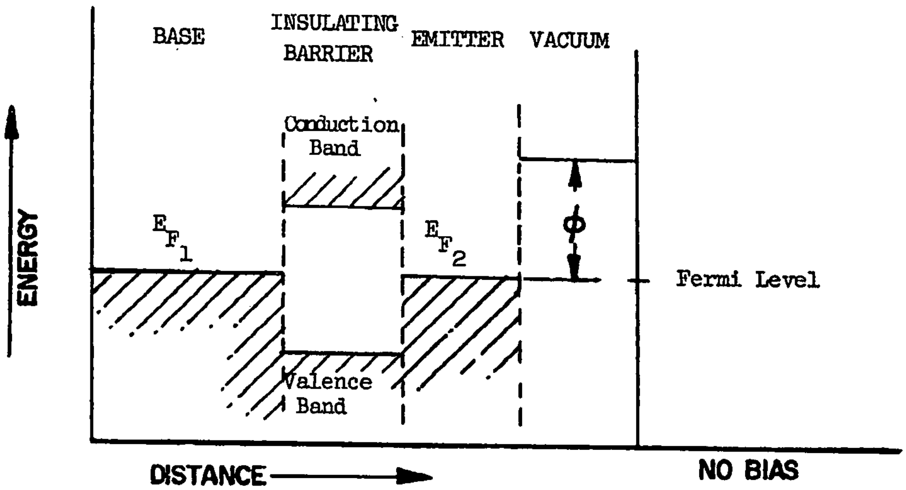
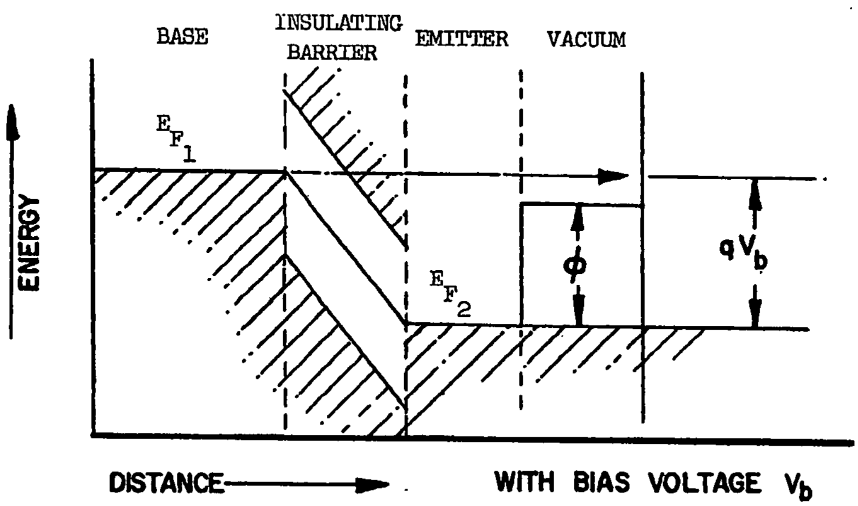

BASE
INSULATING BARRIER
EMITTER
VACUUM
Conduction Band
ENERGY
E_{F_1}
E_{F_2}
ϕ
Fermi Level
Valence Band
DISTANCE
NO BIAS

FIG. 4


BASE
INSULATING BARRIER
EMITTER
VACUUM
ENERGY
E_{F_1}
E_{F_2}
ϕ
qV_b
DISTANCE
WITH BIAS VOLTAGE V_b

1,223,729 COMPLETE SPECIFICATION
3 SHEETS

This drawing is a reproduction of the Original on a reduced scale.
SHEET 3

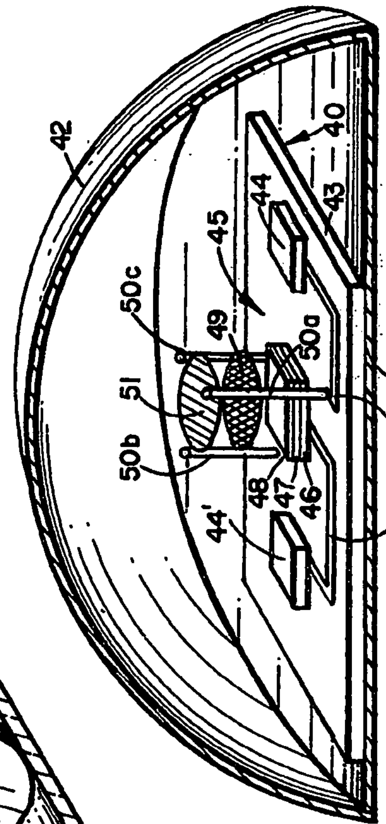


FIG. 5

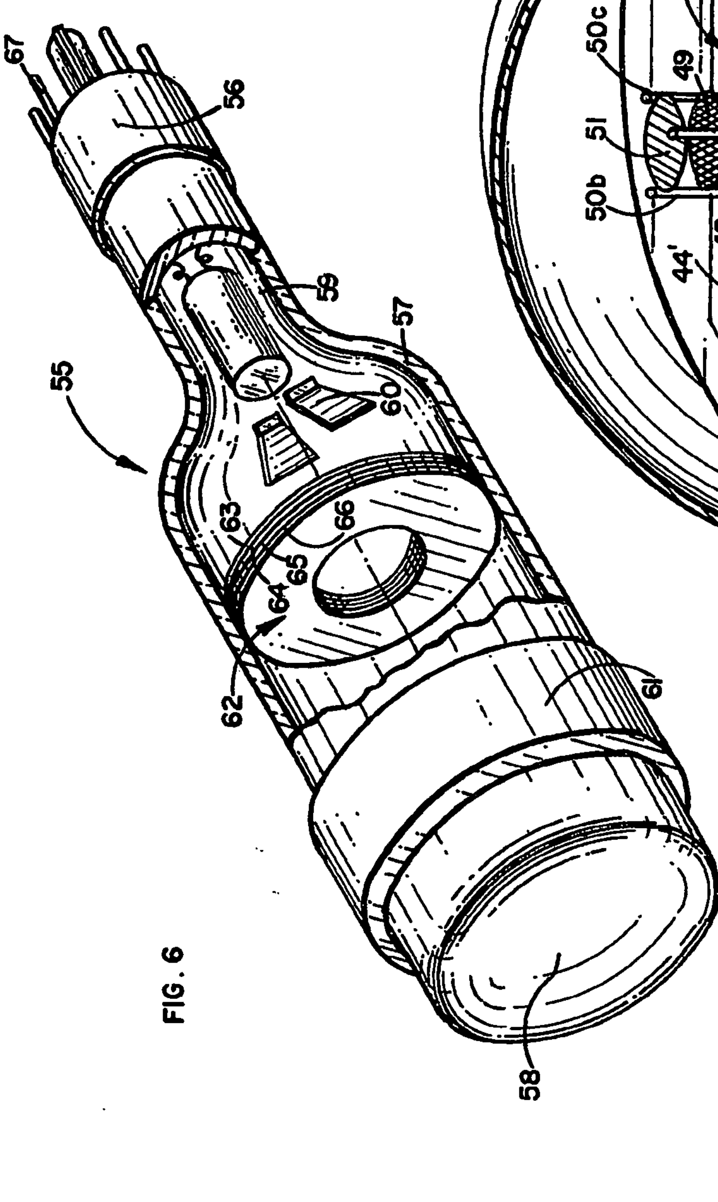


FIG. 6